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THE HIGH-SYPHON CIRCULATING WATER SYSTEM FOR MERAMEC PLANT

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POWER DIVISION

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THE HIGH-SYPHON CIRCULATING WATER SYSTEM FOR MERAMEC PLANT

Chas. E. Buettner,[1] A.M. ASCE, and Paul A. Pickel

SYNOPSIS

Condenser circulating water systems designed for moderate syphon recovery are common. This system was designed to operate with maximum theoretical syphon height. Operating experiences demonstrated that such a system is entirely practical.

A circulating water system for a steam power plant must pass sufficient water through the condensers to condense the steam exhausting from the turbines with a minimum expenditure for pumping power.

Pumping power is a function of the quantity of water pumped and the pumping head. The quantity of water is a function of the expected water temperatures and the heat transfer characteristics of the condenser. The pumping head is the sum of the friction of the water through the system plus any static lift that may be inherent in the system.

The opportunities for substantially reducing the water quantity or friction in any particular case are limited; however, the static head may be completely eliminated or at least very appreciably reduced by "taking full advantage of the syphon."

The design consideration of a system wherein "full advantage of the syphon" was taken—a "high-syphon" system where the designers ventured beyond previously well established limits of design—and the subsequent behavior of the system in actual operation, is the subject of this paper; it is hoped it will be of interest to you.

To sketch very briefly the Plant we are contemplating: Meramec is a steam power plant located on the west bank of the Mississippi River near the mouth of the Meramec some twenty miles south of St. Louis. It presently consists of two Westinghouse turbine generators of 125,000 KW nominal (140,000 KW actual) capacity each operating at 1315 psig - 950° steam pressure with reheat at 455 psig 950°. Steam is supplied to each turbine by a single 925,000 lb. per hour Combustion Engineering Company steam generator.

The steam exhausting from each turbine is condensed in a single, two-pass, divided water box Ingersoll-Rand condenser with 90,000 sq. ft. of heat transfer surface. Approximately 80,000 gallons per minute of river water are passed thru the condenser with a friction drop of 18.5 feet, to condense the 720,000 lb. per hour of steam exhausting from the turbine. The condensing of the steam results in a very low back (or exhaust) pressure on the

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turbine: about 1.2 inches Hg absolute for mean river temperatures. The cooling (circulating) water is raised some 17°F during the process.

Four pumps with a capacity of 45,000 gpm each, located in an intake at the river's edge, pump 180,000 gpm thru a single 96-inch steel line the 1100 ft. to the plant; here some 20,000 gpm are diverted for auxiliary uses and the balance of 160,000 gpm divided between two condensers. The circulating water leaving the condensers is conveyed to the river, to a point downstream of the intake, thru another single 96-inch line. The pipe lines were sized for a velocity of 8 feet per second. The two halves of each condenser, resulting from the division in the water box, are served by their individual supply and outlet pipe branches. These are interconnected with a four-way reversing valve, so that full back washing, that is, complete reversal of the total flow thru the particular half—can be accomplished, to wash away debris that might accumulate on the condenser tube sheets.

Let us now return to the consideration of static head and syphon effect.

Consider a plant located on a body of water that does not vary appreciably in elevation; one of the Great Lakes for instance: the circulating water pumps take suction from this body of water, push it through the system and discharge it back into the Lake through a sealed, that is, a submerged discharge. In this case there is no difference in elevation between the water surfaces between which pumping is taking place; therefore, the static head is zero—provided no part of the system is above the "syphon line."

The "syphon line" may be defined as a line platted vertically above the hydraulic gradient, a distance equal to the difference between the barometric pressure and the vapor pressure of the water being handled, expressed in feet. In this area this distance will be in the neighborhood of 32 feet.

It is an axiom, easily verified by application of Bernoulli's theorem, that if the system profile is platted to the same scale and base as the hydraulic gradient, the vertical distance of any point in the system above the hydraulic gradient is the direct measure of the negative (sub-atmospheric) pressure at the point in feet of liquid being pumped; conversely, the vertical distance of the profile below the hydraulic gradient is a measure of the positive pressure at that point.

Thus, in our hypothetical plant on one of the Great Lakes the highest point in the system—the condenser rear water box perhaps—could be set somewhere in the neighborhood of thirty feet above the water level without increasing the static head.

On the Mississippi, conditions are not that convenient for the designer. At Meramec the Mississippi River has a seasonal variation of about 41 feet: actual variations have been from 368 to 409 mean sea level; and floods up to 418.0 have been anticipated in the design. This poses flood protection problems as well as pumping problems. Pump settings, of course, had to be sufficiently low to assure adequate submergence at the lowest river stage; the impeller center lines are at elevation 362. Logically the main operating floor should be above flood.

The first and obvious possibility was to submerge the discharge in the river below elevation 368 and then to locate the high point of the system vertically as high as possible between the hydraulic gradient and the "syphon line." This would give the most economical pumping arrangement: static pumping head would be eliminated at all river stages and pumping head would consist of friction only. However, this design resulted in the low point of the plant (the basement floor) being at approximate elevation 381, and the excavation for the plant and circulating water piping would in this case be about

20 feet deep. The resulting elevation of the operating floor would be 416: two feet below the design flood.

The original ground at the plant site was at elevation 400 (approximately); and from a structural standpoint the ideal location of the basement floor should be at 403. This elevation would permit construction without excavation, would reduce ballasting of the structure to resist buoyancy, would eliminate water proofing of the structure and eliminate the need to dewater the construction area.

An economic comparison of building costs versus pumping costs for various plant elevations resulted in establishing the basement floor at elevation 400.

An initial system layout was then made with the basement at grade 400 and the condenser located accordingly. The purchase of a condenser of low head room type served by vertical hotwell pumps set into the floor provided a welcomed head reduction. By adopting this low head room type unit and vertical hotwell pumps, it was possible to set the condenser center line five feet lower than initially contemplated. This did not alter the primary objective in the system design, however, which was to take advantage of the maximum possible syphon recovery and thereby reduce pumping requirements at low river stages by reducing static head.

A profile of the system was plotted accurately as shown in Plate I; the two pass condenser was portrayed not as it actually is with the second pass vertically below the first but as if it were a single pass condenser with the downstream half displaced vertically downward from the first pass.

The determination of pressures through the system was accomplished by superposing upon the profile of the proposed system, the hydraulic gradient, as calculated from friction losses in various sections. The gradient was actually drawn backwards from its origin at the river surface near the tail pipe outlet. Thus the origin represented a point of atmospheric pressure, and any other point on the gradient—but not on the profile—was also at atmospheric pressure. As previously mentioned the vertical distance from the gradient to the pipe line profile then represented the actual pressure (above or below atmosphere) at that point in feet of the liquid being handled. By this method it was apparent that the point of lowest absolute pressure for full flow would not be at the condenser centerline (outlet water box) nor at the return water box, but at a point in the outlet pipe some 30 feet beyond the condenser.

This method was also utilized to locate the lowest possible elevation for the tail pipe outlet; with the point of maximum vacuum now located, the gradient was replotted so that it would fall 29.75 feet below the point of maximum vacuum. (See Plate II) Thus, every other point in the system would be under a vacuum less than 29.75 feet. This 29.75 feet is the maximum possible syphon. It is the difference between the lowest expected barometric pressure (28.7 inches Hg) and the vapor pressure of the circulating water at the expected maximum temperature of $107^{o}F$ (2.38) expressed in feet of this $107^{o}F$ water.

A frank and pointed discussion of our use of this value for maximum syphon is given later.

Notice the resulting elevation of the end of the discharge line at elevation 378, about 10 feet above lowest river stage. (Plate II)

The above determination was based on maximum flow conditions, that is, four pumps supplying two condensers. A similar procedure was followed to check performance with two pumps supplying one condenser and also with one pump supplying one condenser. In the latter case it was evident that the maximum vacuum would occur in the return water box of the condenser and that

the tail pipe outlet should be approximately four feet higher in order not to exceed the syphon line. (Plate II) Raising the outlet, however, would impose unnecessary head on the system at maximum flow, which would be the normal condition. What was needed was a seal tank at the outlet having an adjustable weir so that the elevation could be varied to suit flow conditions—something expensive and not too easy to design.

Fortunately that problem was solved incidentally with the solution of another requirement, which involved the means for priming or filling the system initially. Under start-up conditions, before syphon action was established, the very high static head would reduce pump discharge so greatly that water would run out of the long discharge line faster than it could be pumped in; so a 72-inch butterfly valve was installed near the river outlet. (Plate III) It would be a simple matter, then, to fill the system up to the valve, and to establish syphon flow by opening the valve. The valve disc was designed with two 10-inch orifices to act as a permanent by-pass, so that the pumps could never operate at shut-off head and thus develop dangerous pressures in the condenser water boxes. In addition to enabling the system to be primed, the "syphon valve" also permitted the operator to increase friction in the outlet pipe by any amount desired. This has the effect, on the diagram, of raising vertically the portion of the hydraulic gradient, upstream of the valve. (Plate III) For the minimum flow condition of one-pump operation, this gives the same effect as raising the tail pipe elevation, and provides the equivalent of a seal tank having an adjustable weir. Incidentally, the seal was designed as a pipe-trap rather than as a tank. (Plate III)

It is emphasized that the layout for a high syphon system requires very careful and accurate analysis of system friction losses. If losses are overestimated, the gradient slope will be too steep, and will place the outlet too low for successful operation. If they are under-estimated, the outlet will be too high for economical pumping. For the Meramec system, pipe losses were estimated by Hazen and Williams formula for new clean pipe, using a C factor of 140. Friction losses in the many fabricated fittings, and particularly the four-way valve were not quite so easy to estimate, and required considerable judgment. Where possible the Standards at the Hydraulic Institute were used for various fittings. In actual operation, however, friction losses turned out to be gratifyingly close to design estimates.

Stage duration curves of the Mississippi River indicated that it was below this elevation of 378 for 21% of the time. Further investigation revealed that the annual mean stage below elevation 378 was elevation 374.8. Thus with the basement at elevation 400, and the discharge outlet at elevation 378, the pumps would have to pump against 3.18 feet of static head for 76 days of each year.

The excess power required to pump against the inherent static head during this time (with the outlet at elevation 378) would cost about $980.00 per year with flow assumed at 180,000 gpm and energy assumed to cost $.004 per Kwhr.

The cost of lowering the plant elevation below grade 400 in order to eliminate this excess pumping cost was originally estimated at something like $18,000 per foot for the first four feet. At that elevation it was felt that waterproofing would be required, and cost per foot would increase rapidly. The $980.00 excess pumping cost with outlet 10 feet above low water is roughly equal to the carrying charge for lowering the plant one-half foot.

The foregoing conclusion is based quite explicitly on the willingness "to use all of the syphon", that is, to crowd the high point of the system right up to the "syphon line."

It was not without some trepidation that the Meramec designers accepted the practicality of using to the fullest extent the "high syphon" concept. Designers have generally been conservative in determining the head recoverable by a syphon, and in most cases have limited it to around 20 or 22 feet.

At other Company Plants on the same river the maximum syphon did not exceed 17 feet. This included the Venice Plant, until the inception of Meramec, the Company's most modern plant. At Venice the basement level is only 10 feet above the lowest river stage as compared to Meramec which is 32 feet above lowest stage.

At Venice substantial sums were expended for waterproofing, ballasting and dewatering during construction.

There was considerable speculation as to the precise behavior of a large quantity of water, moving at a fair velocity thru a conduit where the pressure varied and closely approached the vapor pressure of the water: would the column separate violently with a resulting disastrous water hammer and then re-unite with equally disastrous force?

During early discussions with condenser manufacturers it was suggested that "syphon efficiency" might be considered as 90% for estimating the recoverable portion of theoretical syphon height. Unfortunately we were not able to find in engineering texts or technical papers any reference which would either substantiate or refute these views.

The only reference found, an English publication, "The Surface Condenser" a Survey of Modern Condenser Practices by B. W. Pendred by Sir Isaac Pitman & Sons, Ltd. London 1935, contended that the water column would probably not rend itself violently but would effervesce into a soda water mixture and proceed almost frivolously thru the system without disaster. This was comforting in that violent destruction of the system was not predicted; but the article did not state how large a conduit was required to transport such a mixture nor did it attempt to define the heat carrying ability of such a substance if effervescence occurred within the condenser.

In spite of references to "syphon efficiency" and the suggestion that 90% of the theoretical height was a practical limit for design and previous limits of design, the calculated figure of 29.75 feet was adopted as the basis for system design. There were two factors which influenced this decision. The first of these was the almost certain knowledge that syphon performance would be impaired primarily by the release of air and gases at high points in the system into large bubbles which would restrict flow. And consequently air removal apparatus of adequate capacity would have to be provided to withdraw these gases as rapidly as they collected. The second was the belief that though the water would tend to vaporize, or "boil" as the syphon limit was reached, turbulence and velocity would keep the vapor distributed thru the water as small bubbles and swept along so that large vapor pockets would not form, and the water column would not break.

The air removal equipment was sized to remove the greatest amount of air that might be occluded from 160,000 gpm of circulating water at 29.75 feet of vacuum. The greatest possible quantity of air contained in the circulating water and consequently occluded when the temperature of the water was increased and the pressure reduced was during the winter months when river water temperatures might go as low as 32^{o}F.

The equipment finally chosen was a pair of 2 stage rotary vacuum pumps for each condenser rated at 579 cfm at a suction pressure of 26 inches Hg.

Initially these pumps took suction from only one point in the system: the top of the rear water box thru a loop, the crown of which was 40 feet higher

than the pumps. The function of this loop was to prevent raw water from being carried into the air removal pumps accidentally during high river stages.

The operation of these pumps was controlled by a float switch operating on water level in their suction pipe. The float chambers were located vertically at an elevation that in this portion of the circulating system should always be flooded provided no air or gases accumulated here. Gases accumulating depressed the water level, lowered the float and started the pumps. The pumps ran for set periods of time determined by a timer. It was felt that the pumps would cycle too frequently if stopped on restoration of water level.

The second pump was rigged like the first but with its float located a bit higher so that it came in to assist its mate if the first pump could not restore level.

It might appear from this that it would be as expensive, to assure a high syphon as to pump against the additional static head. Actually, any system using any degree of syphon requires air removal equipment. The difference is only in the degree to which vacuum or low absolute pressures are produced.

With no air removal equipment it would not be long before any syphon system would become non-syphonic—air bound. This could impose additional pumping head in the magnitude of fifteen to twenty feet at least.

The occasional use of all four air pumps requiring 120 h.p. total is most reasonable when compared to the 56 h.p. required to pump 180,000 gpm against just one foot of additional head.

The construction period between the design and starting stages afforded ample time for the designers—and others—to cogitate on the wisdom of the design. The reactions of associates were interesting: one brightly remarked that even if the design failed utterly it would prove that maybe 24 feet was a sensible limit and thus a small addition would be made to the sum of the world's knowledge.

The actual start-up of the system made with a cold non-operating turbine, i.e., no steam exhausting into the steam space, was so smooth as to be almost disappointing—no drama whatsoever!

A circulating pump was started with the syphon valve in the discharge pipe closed, thus limiting the flow to about 15,000 gpm. The air removal pumps were not operating as the wiring of these devices was still in process.

The backwash valves had been set in the backwash position so that the water would enter the bottom of the condenser and more effectively vent the air out of the manual vents on the front water box.

As the single pump filled the system, solid water began issuing from the vents. These were closed, and the 72-inch syphon valve was opened to establish syphon flow.

Accurate data was not available at this time due to incompleteness of instrumentation; but observed pump discharge pressure indicated that a syphon of about 25 feet had been established.

This phase of start-up was primarily concerned with the intake: screens, pumps, and auxiliaries and the filling of the circulating system. Consequently not too much attention was paid to maintenance of syphon; the concern was in proving the circulator.

With the start-up of the air pumps, syphon was maintained in the system and circulating water pump performance corresponded very closely to design estimates. Initially the only point of air removal from the system was

at the return water box of the condenser, although the pressure shown by the gradient indicated that air would undoubtedly collect at the outlet water box, in the 48-inch discharge pipe, and in the inlet water box. For the first five months of operation, during which the river was at mean stage or higher, vacuum in the water system never exceeded 20 feet, no deficiency of the system was apparent. However, when the river fell to the approximate elevation of the discharge outlet, an abnormal increase in pumping head and reduction of capacity was observed. The clue to the trouble was the large amount of air being discharged into the river at the circulating water outlet. At this time only the first unit was operating, and velocity in the 96-inch pipes was only half the design velocity. Apparently released air was being purged from the 48-inch connections by the 8 fps velocity, but on entering the 96-inch return header it began to collect along the top of the pipe. This long horizontal header formed an ideal pocket, and the size of the air bubble increased, restricting flow until a condition of equilibrium was reached.

The air pumps are installed on the opposite side of the turbine room from the circulating water pipes and condenser connections. In the initial design of the air removal system the possibility of certain high spots or "pockets" in these areas trapping air or gases and thereby reducing the syphon were considered. Air removal piping for systems on turbid rivers can be expensive: all portions subject to flooding should be vertical or slope sharply; horizontal lines "mud up" and render the system inoperative. These pockets would require lines going vertically up, then crossing the turbine room at the roof to clear the crane before connecting into the air pump suctions. These pockets were not real traps—they were "fair," to use a shipbuilder's term and it was strongly felt that any gases accumulating in these places would be swept away.

So in the interest of economy and because the need did not appear imperative we did not vent these pockets and in this we were in error: the very "fairness" did not promote sweeping at all—some of the gases may have been trapped and swept along if there had been more turbulence in these areas.

A 4-inch air removal connection was installed, and the high points of the return header, and of the 48-inch condenser discharge lines were tied in to the vacuum pump suction. Normal operation of the circulating system resulted. As a further precaution, the outlet and inlet water boxes were also connected to the vacuum pump; although some additional improvement was noted, it was obvious that the greatest benefit resulted from the connection on the 96-inch pipe. Vacuum pumps had plenty of capacity—it was just a matter of connecting them to the air pockets.

Subsequent operation provided ample opportunity to observe the high syphon system under the most adverse conditions. Beginning in September 1953, the river stage fell below zero and except for a few days, remained below zero until February 1954. Whereas the normal expectancy is 11 days per year at zero and below, there were 120 days in that range during the 1953-54 winter. The extreme low occurred on January 28, 1954, at which time the river fell to within 3 inches of the all-time record.

Starting in November 1953, condenser performance, as indicated by turbine back pressure, became progressively worse. This seemed to indicate a greatly reduced circulating water flow, and was naturally attributed to poor efficiency of the syphon system at low river stages. A thorough investigation then was undertaken, showing that all parts of the circulating system were functioning normally, except that pressure loss across the condenser was about 28 feet. For the amount of water flowing at the time, pressure drop

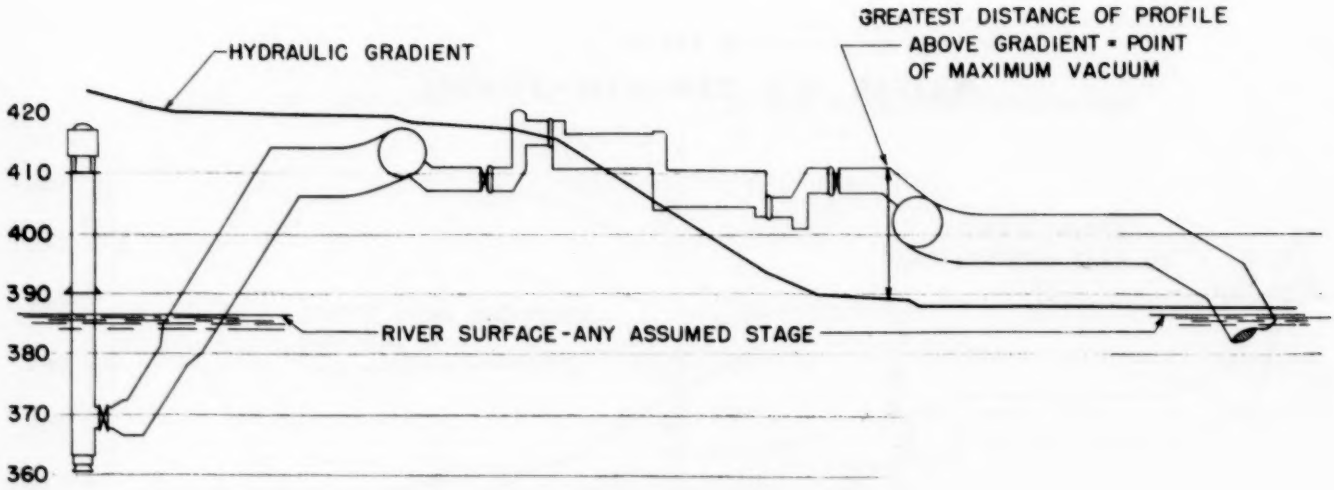
should have been around 14 feet. Inspection of the condenser disclosed that tubes were severely fouled with a thick coating of slime. After the condenser was cleaned, turbine back pressure dropped from 1.40" Hg to 0.73". Fortunately, these troubles occurred while river temperatures were low, and it was never necessary to reduce load on account of inadequate circulating water.

Subsequently this fouling was eliminated by chlorinating the circulating water supply.

Looking backward, it now seems that our fears in setting out to design a high-syphon system were groundless. From the original concept of a column of water supporting itself for 29.75 feet, but breaking and slamming together with terrific shock and vibration when that height was exceeded, we progressed to the "soda water" concept, wherein bubbles occur, forming a water-vapor mixture of less density, which could be supported at a greater height by atmospheric pressure. In the case of Meramec, with long horizontal lines of large diameters, it now seems more logical to visualize the water level as rising or falling in accordance with the existing pressures. For example, if the gradient indicates that vacuum at a certain point should be 32 feet, but atmospheric pressure will only support 29 feet, water surface in the pipe will merely fall 3 feet. The vacated space would fill with air if air is in solution, or with vapor if the water is air-free. Since the condition now simulates open channel flow, with reduced cross section, friction in this part of the system increases and raises the hydraulic gradient. Pump must produce additional head to overcome the added friction, and a condition of equilibrium at a somewhat lower flow is reached.

It is significant to note that actual operation of this high syphon system has been very close to the performance predicted during the design stage. During the early months, while condenser was relatively clean, pumping head varied between 28 and 31 feet, as compared with the estimated system friction of 30.19 feet. During the months of low river stage, the "vacuum top of syphon" has consistently shown 25.5"Hg, corresponding to a syphon of 28.9 feet. To our knowledge there has never been an instance of inadequate circulating water (except the case described herein) which could be attributed to poor performance of the syphon system.

In conclusion we are of the opinion that the theoretical maximum syphon is obtainable and introduces no operating hazards; however, the maximum practical syphon limit is determined by the commercial limits of air removal equipment.



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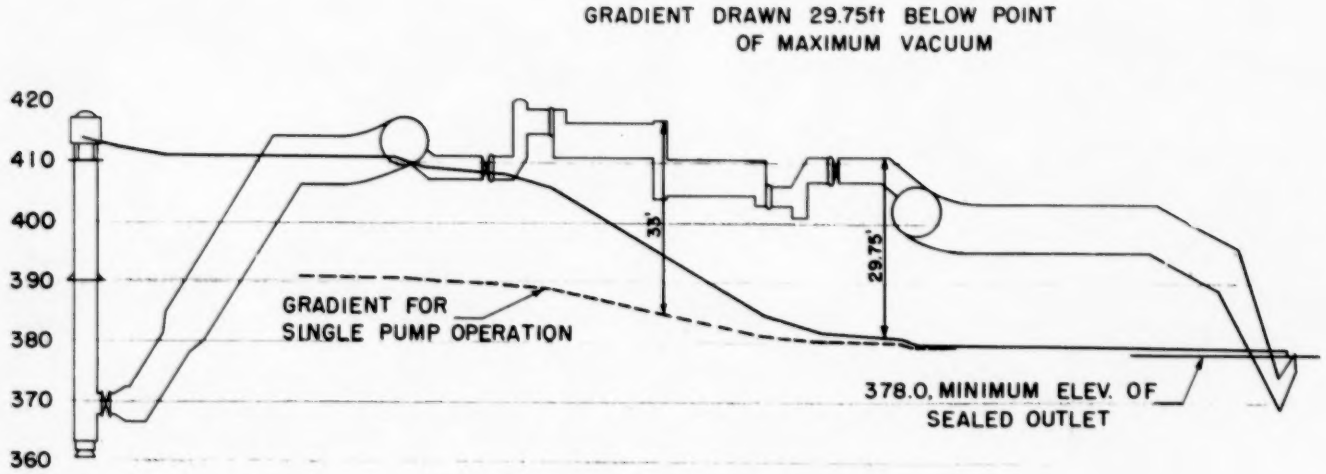
PROFILE - MERAMEC C.W. SYSTEM

PLATE I



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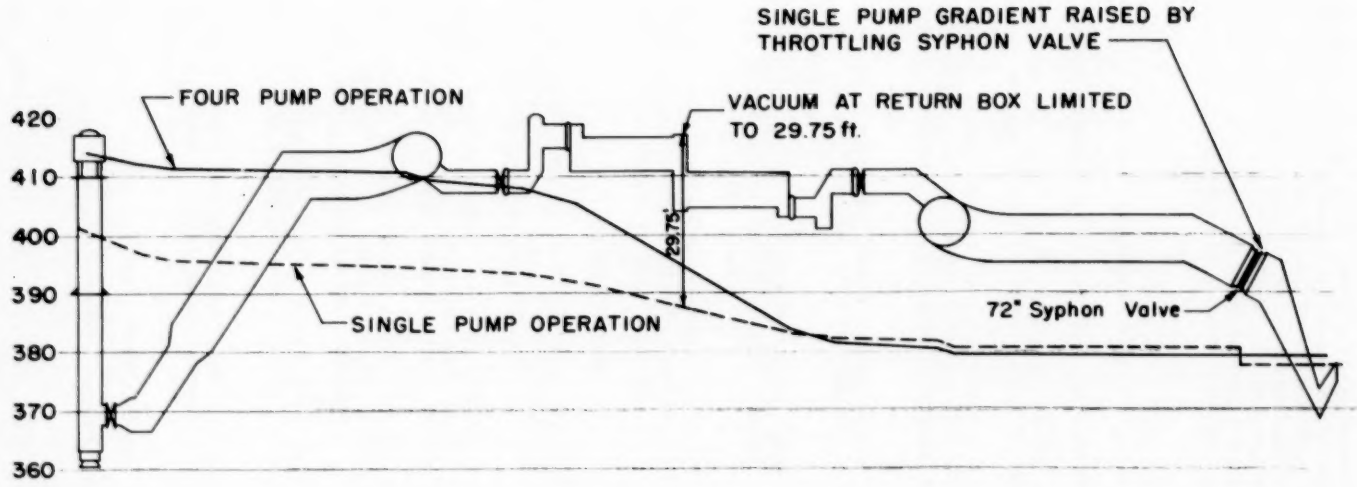
PROFILE - MERAMEC C.W. SYSTEM

PLATE II



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PROFILE - MERAMEC C.W. SYSTEM

PLATE III

PROCEEDINGS PAPERS

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

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MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(SU).

JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

c. Discussion of several papers, grouped by Divisions.

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